

Chapter 9

Summary and Conclusion

conclusion-chap
2 The preceding chapters of this document describe the design of the Long-Baseline Neutrino Experiment, its technical capabilities, and the breadth of physics topics at the forefront of particle and astrophysics the experiment can address. This chapter concludes the document with several discussions that look forward in time, specifically:

- 1 1 a consideration of how the design and construction of the LBNE experiment might unfold
1 from this point on for a general class of staging scenarios,
- 1 1 a summary of the grand vision for the science of LBNE and its potential for transformative
1 discovery,
- 1 2 a summary of the compelling reasons — such as LBNE’s current advanced state of technical
2 development and planning, and its alignment with the national High Energy Physics (HEP)
3 program — for which *LBNE represents the world’s best chance for addressing this science*
4 *on a reasonable timescale*,
- 5 6 comments on the broader impacts of LBNE, including the overarching benefits to the field
6 of HEP, both within and beyond the U.S. program.

9.1 LBNE Staging Scenarios and Timeline

taging-timeline
7 With DOE CD-1 (“Alternate Selection and Cost Range”) approval in hand, the LBNE Project is working toward its technical design specifications, including detailed costs and schedule, in preparation for CD-2 (“Performance Baseline”). It should be noted that the Project already has fully developed schedules for both the CD-1 scope (10-kt far detector on the surface at the Sanford Underground Research Facility, no near neutrino detector), and for the full-scope (34-kt far detector located deep underground and near neutrino detector) for the scenario of funding solely from DOE. Partnerships with non-DOE groups are being sought to enable the construction of LBNE with a near neutrino detector and an underground far detector mass greater than 10 kt in the first phase.

9
sec:global-partner
10 Section I.2.3 described the substantial progress that has been achieved so far toward making LBNE
11 a fully international project. While the specific form and timing of contributions from new partners
12 are not yet known, there are several plausible scenarios in which the Project can be implemented to
13 accommodate non-DOE contributions. A review of the DOE project milestones, indicating where
14 flexibility and potential for incorporating non-DOE contributions exist, provides a starting point.

- 15 DOE-funded projects are subject to several *critical decision (CD)* milestones as shown in Figure 9.1 and explained in DOE Order O 413.3B [344]. At CD-2 the first-phase LBNE Project will

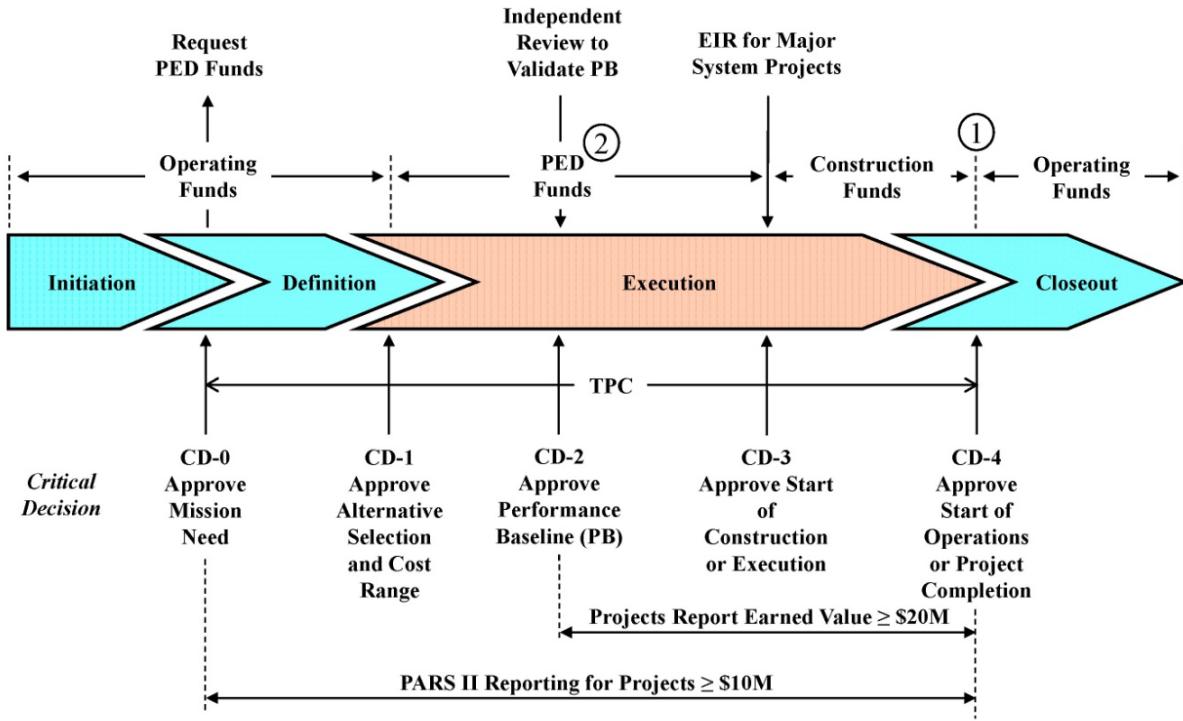


Figure 9.1: Typical DOE Acquisition Management System for line item capital asset projects [344].

16
17 be baselined. Currently, the timescale for CD-2 is projected to be toward the end of FY 2016, al-
18 though the DOE has indicated flexibility in the project approval process specifically to allow for
19 incorporation of scope changes enabled by additional partners. For example, it has been suggested
20 that the design and construction approval for different portions of the Project can be approved at
21 different times to facilitate proper integration of international partners. It is also expected that CD-
22 3a approval (start of construction/execution) may take place for some parts of the Project before
23 CD-2, thereby authorizing expenditures for long-leadtime components and construction activities,
24 such as the advanced site preparation at Fermilab for the new beamline. The CD-4 milestone (com-
25 pletion of the construction project and transition to experiment operations) is currently projected
26 for 2025. However, it is expected that commissioning and operations for LBNE will have started
27 approximately a year before CD-4, which is considered the formal termination of the construction
28 project.

29 The actual timeframe for achieving LBNE science goals will depend on the manner in which
30 a complex sequence of developments takes place, including the actions of partners as well as

³¹ implementation of the milestones above for the DOE-funded elements of the Project. Various
³² scenarios for incorporating contributions from new partners/sources of funding have been iden-
³³ tified [345].
³⁴

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Using the current understanding of DOE funding profiles, we outline one plausible long-term timeline that integrates evolution of LBNE detector mass with development of the Fermilab accelerator complex (i.e., PIP-II) and contributions from non-DOE partners. Implicit in this timeline is an assumption that agreements with new partners be put in place on a timescale of three years (by 2017). In this scenario, the milestones that bear on the physics are as follows:

1. LBNE begins operation in 2025 with a 1.2-MW beam and a 15-kt far detector. (In such a scenario, a significant fraction of the far detector mass might be provided in the form of a standalone LArTPC module developed, funded, and constructed by international partners.)
2. Data are recorded for five years, for a net exposure of $90 \text{ kt} \cdot \text{MW} \cdot \text{year}$.
3. In 2030, the LBNE far detector mass is increased to 34 kt, and proton beam power is increased to 2.3 MW.
4. By 2035, after five years of additional running, a net exposure of $490 \text{ kt} \cdot \text{MW} \cdot \text{year}$ is attained.

³⁵

³⁶ Physics considerations will dictate the desired extent of operation of LBNE beyond 2035.

³⁷ This very coarse timeline is indicative of the degree of flexibility available for the staging of various
³⁸ elements of LBNE. For example, near detector construction (and the corresponding funding) could
³⁹ be undertaken by partners outside the U.S., on a timescale driven by the constraints they face, and
⁴⁰ could be completed somewhat earlier or later than the far detector or beamline.

⁴¹ With this timeline as a guide, the discussion of LBNE physics milestones can be anchored by
¹ plausible construction scenarios.

2 9.2 Science Impact

3 While considering the practical challenges implicit in the discussion in Section 9.1 for the realization
 4 of LBNE, it is important to reiterate the compelling science motivation in broad terms.
 5 The discovery that neutrinos have mass constitutes the only palpable evidence *within the body*
 6 *of particle physics data* that the Standard Model of electroweak and strong interactions does not
 7 describe all observed phenomena. In the Standard Model, the simple Higgs mechanism — now
 8 confirmed with the observation of the Higgs boson — is responsible for quark as well as lepton
 9 masses, mixing and CP violation. Puzzling features such as the extremely small masses of neutrinos
 10 compared to other fermions and the large extent of mixing in the lepton sector relative to the quark
 11 sector, suggest that new physics not included in the current Standard Model is needed to connect
 12 the two sectors. These discoveries have moved the study of neutrino properties to the forefront of
 13 experimental and theoretical particle physics as a crucial tool for understanding the fundamental
 14 nature and underlying symmetries of the physical world.
 15

The measurement of the neutrino mass hierarchy and search for CP violation in LBNE will further clarify the pattern of mixing and mass ordering in the lepton sector and its relation to the patterns in the quark sector. The impact of exposures of $90 \text{ kt} \cdot \text{MW} \cdot \text{year}$ (2030) and $490 \text{ kt} \cdot \text{MW} \cdot \text{year}$ (2035) for Mass Hierarchy and CP-violation signatures is easily extracted from Figure 4.16. Should CP be violated through neutrino mixing effects, the typical signal in LBNE establishing this would have a significance of at least three (2030) and five standard deviations (2035), respectively for 50% of δ_{CP} values (and greater than three standard deviations for nearly 75% of δ_{CP} by 2035). In such a scenario, the mass hierarchy can be resolved with a sensitivity for a typical experiment of $\sqrt{\Delta\chi^2} \geq 6$ for 50% (100%) of δ_{CP} by 2030 (2035).

16

17 If CP is violated maximally with a CP phase of $\delta_{\text{CP}} \sim -\pi/2$ as hinted at by global analyses
 18 of recent data [69], the significance would be in excess of 7σ . This opportunity to establish the
 19 paradigm of leptonic CP violation is highly compelling, particularly in light of the implications for
 20 leptogenesis as an explanation for the Baryon Asymmetry of the Universe (BAU). With tight con-
 21 trol of systematic uncertainties, additional data taking beyond 2035 would provide an opportunity
 22 to strengthen a marginally significant signal should δ_{CP} take a less favorable value.

23 Similarly, the typical LBNE data set will provide evidence for a particular mass ordering by 2030
 24 in the scenario described in Section 9.1, and will exclude the incorrect hypothesis at a high degree
 25 of confidence by 2035, over the full range of possible values for δ_{CP} , θ_{23} and the mass ordering
 26 itself. In addition to the implications for models of neutrino mass and mixing directly following
 27 from this measurement, such a result could take on even greater importance. Should LBNE exclude
 28 the normal hierarchy hypothesis, the predicted rate for neutrinoless double-beta decay would then

29 be high enough so as to be accessible to the next generation of experiments [346]. A positive result
1 from these experiments would provide unambiguous — and exciting — evidence that neutrinos
2 are Majorana particles*, and that the empirical law of lepton number conservation — a law lacking
3 deeper theoretical explanation — is not exact. Such a discovery would indicate that there may be
4 heavier sterile right-handed neutrinos that mix with ordinary neutrinos, giving rise to the tiny ob-
5 served neutrino masses as proposed by the seesaw mechanism [67]. On the other hand, a rejection
6 of the normal neutrino mass hierarchy by LBNE coupled with a null result from the next genera-
7 tion of neutrinoless double-beta decay experiments would lead to the conclusion that neutrinos are
8 purely Dirac particles. This would be a profound and astonishing realization, since it is extremely
9 difficult theoretically to explain the tiny masses of Dirac neutrinos. High-precision neutrino os-
10 cillation measurements carried out by LBNE beyond 2035 may provide evidence for Majorana
11 neutrino mass effects that are outside of the ordinary Higgs mechanism or for new interactions that
12 differentiate the various neutrino species.

13 Within the program of underground physics, LBNE’s most exciting milestones would correspond
14 to observations of rare events. By 2035, LBNE will have been live for galactic supernova neutrino
15 bursts for ten years in the above scenario. Such an event would provide a spectacular data set that
16 would likely be studied for years and even decades to follow.

17 For proton decay, the net exposure obtained by 2035 in the above scenario also provides a com-
18 pelling opportunity. A partial lifetime for $p \rightarrow K^+ \bar{\nu}$ of 1×10^{34} years, beyond the current limit
19 from Super-Kamiokande by roughly a factor of two, would correspond to six candidate events
20 in LBNE by 2035, with 0.25 background events expected. Running for seven more years would
21 double this sample. (Similarly, one should not ignore the corresponding value of an LBNE con-
22 struction scenario that has a larger detector mass operating from the start, in 2025). With careful
23 study of backgrounds, it may also be possible to suppress them further and/or relax fiducial cuts to
24 gain further in sensitivity.

25 Finally, the proposed high-resolution near detector, operating in the high-intensity LBNE neutrino
26 beam, will not only constrain the systematic errors that affect the oscillation physics but will also
27 conduct precise and comprehensive measurements of neutrino interactions — from cross sections
28 to electroweak constants.

29 9.3 Uniqueness of Opportunity

30 Considering the time and overall effort taken to reach the current state of development of LBNE,
31 it will be challenging for alternative programs of similarly ambitious scope to begin operation be-
32 fore 2025, particularly in light of the current constrained budget conditions in HEP. It should be
33 noted that similar-cost alternatives for the first phase of LBNE utilizing the existing NuMI beam

*A Majorana particle is an elementary particle that is also its own antiparticle

³⁴ were considered during the reconfiguration exercise in 2012 [25]. The panel concluded that none
³⁵ of these alternatives presented a path toward an experiment capable of a CP-violation signal of
³⁶ 5σ . Furthermore, a large water Cherenkov far detector option for LBNE was carefully considered
³⁷ prior to selection of the LArTPC technology [347]. While both detector options are capable of sat-
¹ isfying the scientific requirements, the LArTPC was judged to have a better potential for scientific
² performance while also presenting the attraction of an advanced technological approach.

³ In the broader context of planned experimental programs with overlapping aims for portions of the
⁴ LBNE science scope, it must be recognized that progress will be made toward some of these during
⁵ the period before LBNE operations commence. For example, indications for a preferred neutrino
⁶ mass ordering may emerge from currently running experiments and/or from dedicated initiatives
⁷ that can be realized on a shorter timescale. Global fits will continue to be done to capitalize, to
⁸ the extent possible, on the rich phenomenology of neutrino oscillation physics where disparate
⁹ effects are intertwined. At the same time, each experimental arena will be subject to its own set of
¹⁰ systematic uncertainties and limitations.

¹¹ It is in this sense that the power of LBNE is especially compelling. LBNE will on its own be able
¹² to measure the full suite of neutrino mixing parameters, and with redundancy in some cases. To
¹³ use the MH example just given, it is notable that LBNE will have sensitivity both with beam and
¹⁴ atmospheric neutrinos. Control of the relative $\nu_\mu/\bar{\nu}_\mu$ content of the beam as well as the neutrino
¹⁵ energy spectrum itself, provides additional handles and cross-checks absent in other approaches.

¹⁶ 9.4 Broader Impacts

¹⁷ 9.4.1 Intensity Frontier Leadership

¹⁸ The U.S. HEP community faces serious challenges to maintain its vibrancy in the coming decades.
¹⁹ As is currently the case with the LHC, the next-generation energy frontier facility is likely to be
²⁰ sited outside the U.S. It is critical that the U.S. host facilities aimed at pursuing science at the
²¹ HEP scientific frontiers (Figure ^{fig:frontiers} 3.1), the lack of which could result in erosion of expertise in key
²² technical and scientific sectors (such as accelerator and beam physics).
²³

LBNE represents a world-class U.S.-based effort to address the science of neutrinos with technologically advanced experimental techniques. By anchoring the U.S. Intensity Frontier program [348], LBNE provides a platform around which to grow and sustain core infrastructure for the community. Development of the Fermilab accelerator systems, in particular, will not only advance progress toward achieving the science goals of LBNE, it will also greatly expand the capability of Fermilab to host other key experimental programs at the Intensity Frontier.

25 9.4.2 **Inspirational Project for a New Generation**

26 Attracting young scientists to the field demands a future that is rich with ground-breaking scientific
27 opportunities. LBNE provides such a future, both in the technical development efforts required and
28 its physics reach. The unparalleled potential of LBNE to address fundamental questions about the
29 nature of our Universe by making high-precision, unambiguous measurements with the ambitious
30 technologies it incorporates will attract the best and brightest scientists of the next generation to
31 the U.S. HEP effort.

32 A young scientist excited by these prospects can already participate in current experiments — some
33 of which use medium-scale LArTPCs — and make contributions to leading-edge R&D activities
34 that provide important preparation for LBNE, both scientifically and technically.

35 **9.5 Concluding Remarks**

36

Understanding the fundamental nature of fermion flavor, the existence of CP violation in the lepton sector and how this relates to the Baryon Asymmetry of the Universe; knowing whether proton decay occurs and how; and elucidating the dynamics of supernova explosions all stand among the grand scientific questions of our times. The bold approach adopted for LBNE provides the most rapid and cost-effective means of addressing these questions. With the support of the global HEP community, the vision articulated in this document can be realized in a way that maintains the level of excitement for particle physics and the inspirational impact it has in the U.S. and worldwide.

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